Neutron-Antineutron Oscillation Experiments

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Project X Workshop

Why do we think that B is violated?

Neutron-antineutron oscillations in nuclei

Free neutron oscillations

Experimental requirements

Thanks for slides: Tony Mann, Yuri Kamyshkov, Ed Kearns,…

$n \leftrightarrow \bar{n}$ oscillations — are they “too crazy”?

But neutral meson $|q\bar{q}\rangle$ states oscillate -

$$K^0, B^0 \longleftrightarrow \left[\,2^{nd}\text{ order weak}\,\right] \longleftrightarrow \overline{K^0}, \overline{B^0}$$

And neutral fermions can oscillate too -

$$\nu_\mu \longleftrightarrow \left[\,\ldots\,\right] \longleftrightarrow \nu_e$$

So why not -

$$n \longleftrightarrow \left[\,\text{New physics}\,\right] \longleftrightarrow \bar{n} \quad ?$$

Neutron is a long-lived neutral particle ($q_n < 10^{-21}e$) and can oscillate into an antineutron. No oscillations have been seen yet.

Need interaction beyond the Standard Model that violates Baryon number (B) by 2 units. No experimental observation of B violation yet. Should we expect B violation?

B,L are Probably Not Conserved

No evidence that either B or L is locally conserved like Q: where is the macroscopic B/L force? (not seen in equivalence principle tests).

Baryon Asymmetry of Universe (BAU) is not zero. If B(t=after inflation)<<BAU (otherwise inflation is destroyed, Dolgov/Zeldovich), we need B violation.

Both B and L conservation are “accidental” global symmetries: given $SU(3)\otimes SU(2)\otimes U(1)$ gauge theory and matter content, no dimension-4 term in Standard Model Lagrangian violates B or L in perturbation theory.

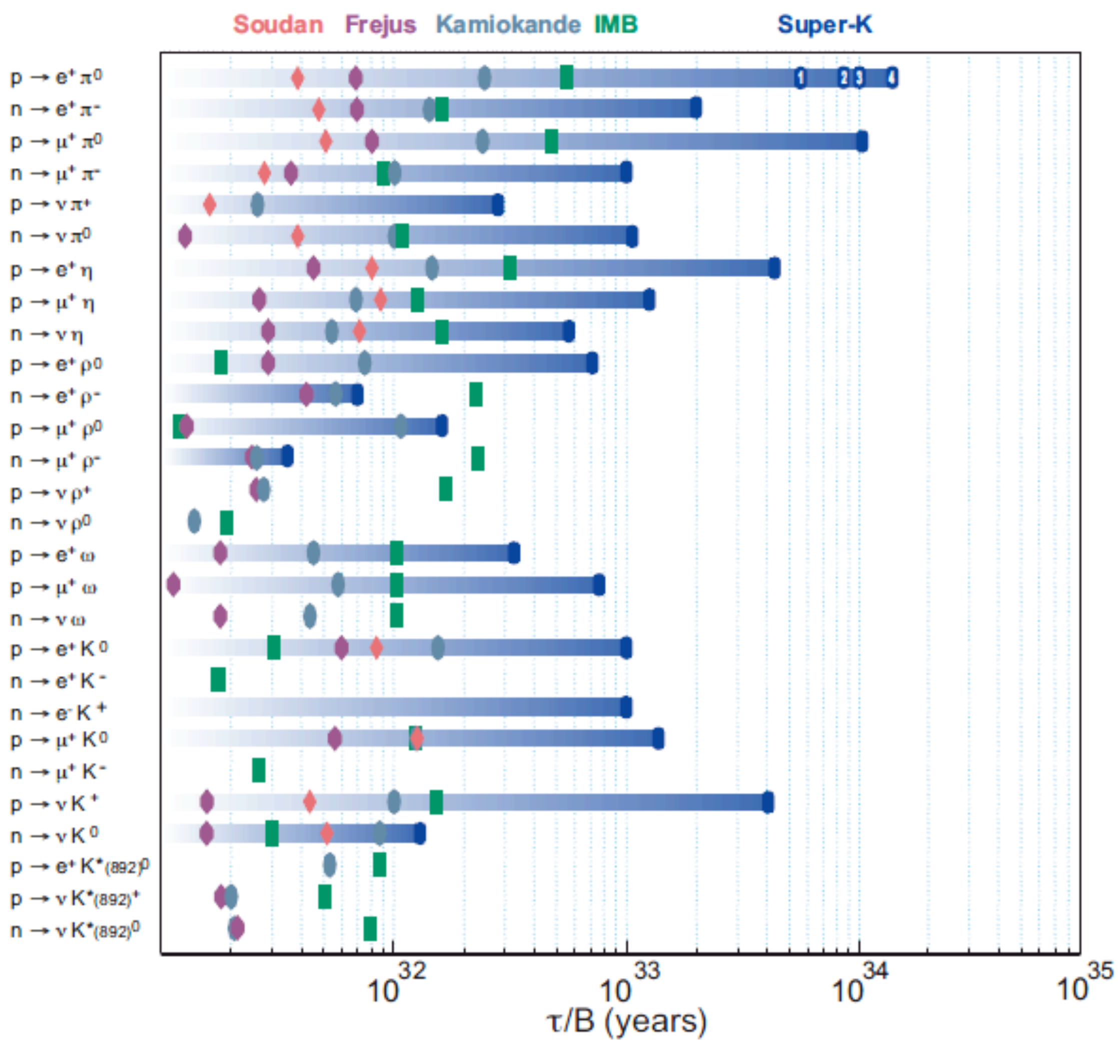
Nonperturbative EW gauge field fluctuations (sphalerons) present in SM, VIOLATE B, L, B+L, but conserve B-L. Very important process for trying to understand the physics of the baryon asymmetry in the early universe

How to search for B violation experimentally?

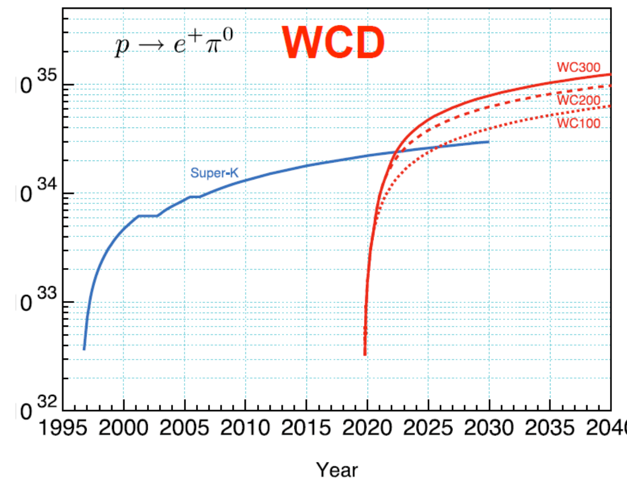
Searches for B Violation (Nucleon Decay and Neutron-Antineutron Oscillation) Probe Different Physics

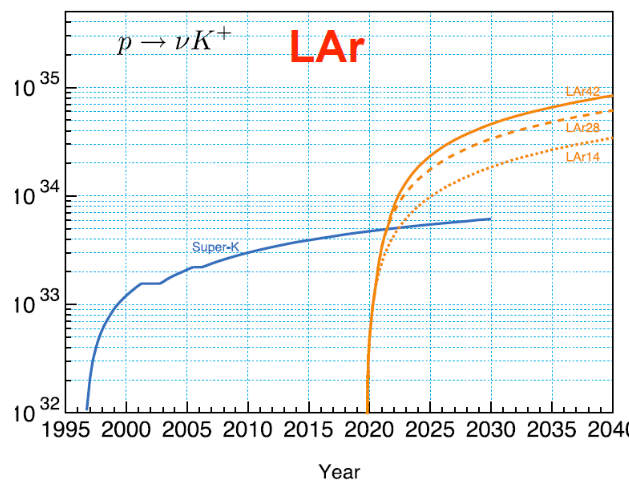
Mode	Nucleon decay	N-Nbar oscillations
effect on B and L	$\Delta B=1$, $\Delta L=1$, others <u>$\Delta(B\text{-}L)=0,2,\ldots$</u>	$\Delta B=2$, $\Delta L=0$, <u>$\Delta(B\text{-}L)=2$</u>
Effective operator	$L=\frac{g}{M^2}QQQL$	$L=\frac{g}{M^5}QQQ\overline{Q}\,\overline{Q}\,\overline{Q}$
Mass scale probed	Grand Unified (GUT) scale	>electroweak scale (<<GUT)

Nucleon Decay



J. L. Raaf @ IF-2011

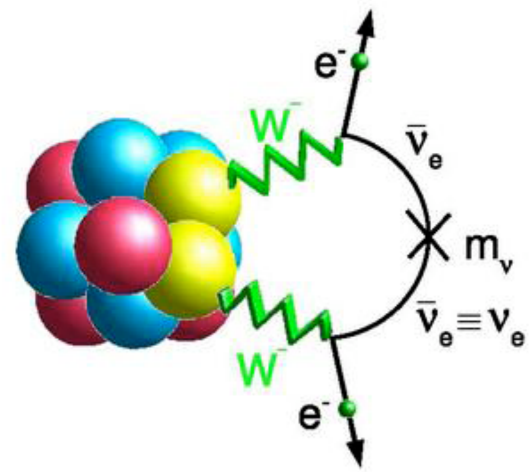




LBNE Physics Working Group Report
arXiv:1110.6249v1 [hep-ex]

Connection of ΔB=2 processes to neutrino physics

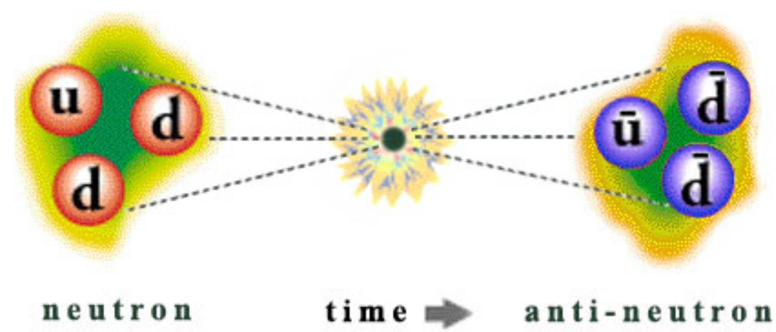
- Several experiments are currently searching for Majorana neutrinos in neutrinoless double beta decay. Neutrinoless double beta decay means ΔL = 2, thus violating (B-L) by 2.



$$\nu \leftrightarrow \overline{\nu}$$

- If (B-L) is violated by 2 and quark-lepton unification happens then ΔB=2 and thus neutron-antineutron oscillations should exist

$$n \leftrightarrow \overline{n}$$



- How are neutron-antineutron oscillations described?

Neutron-Antineutron Oscillations: Formalism

$\alpha \neq 0$ allows oscillations

$$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$ n-nbar state vector

$$\mathrm{H} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

Neutron-Antineutron transition probability

For $H = \begin{pmatrix} E+V & \alpha \\ \alpha & E-V \end{pmatrix}$ $\qquad P_{n\to\bar{n}}(t) = \dfrac{\alpha^2}{\alpha^2+V^2} \times \sin^2\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar}t\right]$

where V is the potential difference for neutron and anti-neutron.

Present limit on $\alpha \le 10^{-23} eV$

Contributions to V:

<Vmatter>~100 neV, proportional to density

<Vmag>=μB, ~60 neV/Tesla; B~10nT-> Vmag~10^{-15} eV

<Vmatter> , <Vmag> both >>α

For $\left[\dfrac{\sqrt{\alpha^2+V^2}}{\hbar}t\right] << 1$ ("quasifree condition") $\qquad P_{n\to\bar{n}} = \left(\dfrac{\alpha}{\hbar}\times t\right)^2 = \left(\dfrac{t}{\tau_{n\bar{n}}}\right)^2$

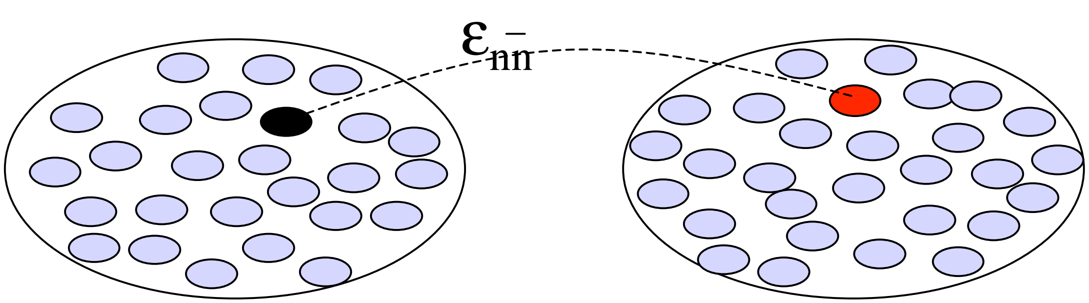
Figure of merit= NT^2 N=#neutrons, T="quasifree" observation time

How to Search for N-Nbar Oscillations

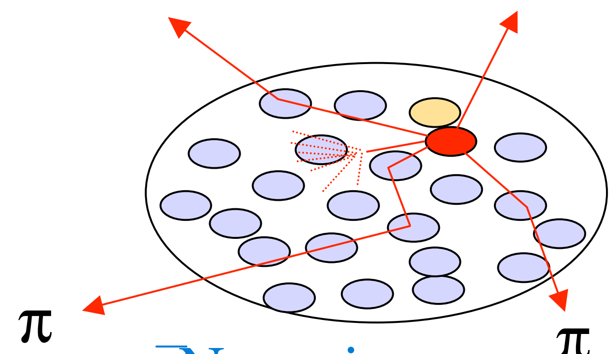
Figure of merit for probability: $$NT^2$$
N=total # of free neutrons observed
T= observation time per neutron while in “quasifree” condition

When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short
B field must be suppressed to maintain quasifree condition due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors
(2) Cold and Ultracold neutrons



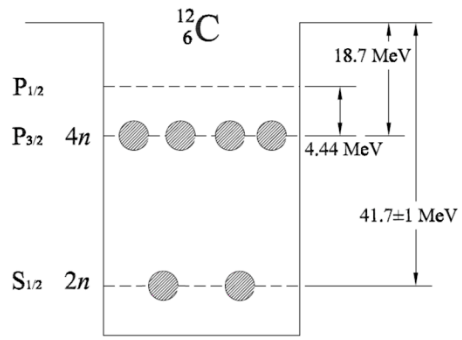
Nucleus A $\rightarrow$ A* + $\bar{\text{n}}$



$\bar{\text{n}}$N $\rightarrow$ pions

Suppression of n→nbar in intranuclear transitions

Neutrons inside nuclei are "free" for the time: $\Delta t \sim \dfrac{\hbar}{E_{binding}} \sim \dfrac{\hbar}{30MeV} \sim 4.5 \times 10^{-22} s$



each oscillating with "free" probability $= \left(\dfrac{\Delta t}{\tau_{n\bar{n}}}\right)^2$

and "experiencing free condition" $N = \dfrac{1}{\Delta t}$ times per second.

Transition probability per second: $P_A \doteq \dfrac{1}{\tau_A} = \left(\dfrac{\Delta t}{\tau_{n\bar{n}}}\right)^2 \times \left(\dfrac{1}{\Delta t}\right)$

Intranuclear transition (exponential) lifetime: $\boxed{\tau_{\mathrm{A}} = \dfrac{\tau_{n\bar{n}}^2}{\Delta t} = R \leftrightarrow \tau_{n\bar{n}}^2}$

where $\mathrm{R} \sim \dfrac{1}{\Delta \mathrm{t}} \sim 4.5 \leftrightarrow 10^{22} s^{-1}$ is "nuclear suppression factor"

Actual nuclear theory suppression calculations for $^{16}O, ^{2}D, ^{56}Fe, ^{40}Ar$ by C. Dover et al; W.Alberico et al; B.Kopeliovich and J. Hufner, and most recently by Friedman and Gal (2008) corrected this rough estimate within a factor of 2

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Realistic calculations of nuclear disappearance lifetimes induced by $n\bar{n}$ oscillations

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Realistic calculations of nuclear disappearance lifetimes induced by $n\bar{n}$ oscillations are reported for oxygen and iron, using $\bar{n}$ nuclear potentials derived from a recent comprehensive analysis of $\bar{p}$ atomic X-ray and radiochemical data. A lower limit $\tau_{n\bar{n}} > 3.3 \times 10^8$ s on the $n\bar{n}$ oscillation time is derived from the Super-Kamiokande I new lower limit $T_d(\mathrm{O}) > 1.77 \times 10^{32}$ yr on the neutron lifetime in oxygen. Antineutron scattering lengths in carbon and nickel, needed in trap experiments using ultracold neutrons, are calculated from updated $\bar{N}$ optical potentials at threshold, with results shown to be largely model independent.

DOI: 10.1103/PhysRevD.78.016002 PACS numbers: 11.30.Fs, 13.75.Cs, 36.10.Gv

General approach: one of the neutrons in the nucleus transforms to anti-neutron and the latter is annihilated with other nucleons to pions

Vacuum N-Nbar transformation from bound neutrons:

Best result so far from Super-K in Oxygen-16

$$\boxed{\tau_{^{16}O} > 1.89 \leftrightarrow 10^{32}\, yr \quad (90\%\ \mathrm{CL})}$$

$\Re$ 24 observed candidates;
24.1 exp. background

$$\boxed{\tau_{nucl} = R \times \tau^2_{n\bar{n}\ \mathrm{free}}}$$

$$\text{if } R_{^{16}O} = 5 \cdot 10^{22}\, s^{-1} \quad \text{(from Friedman and Gal 2008)}$$

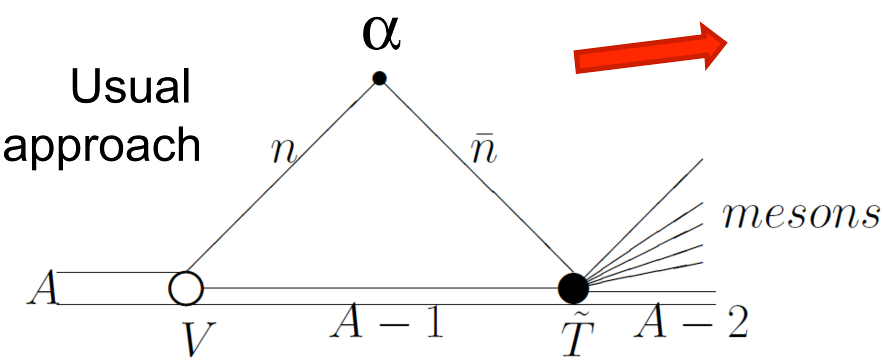
$$\Rightarrow \tau(\text{from bound}) > 3.5 \times 10^{8}\, s \quad \text{or} \quad \alpha < 2 \times 10^{-24}\, eV$$

↔16 times higher than sensitivity of ILL expt.

ILL limit (1994) for free neutrons: $\tau_{n\bar{n}} > 0.86 \times 10^{8}\, s$

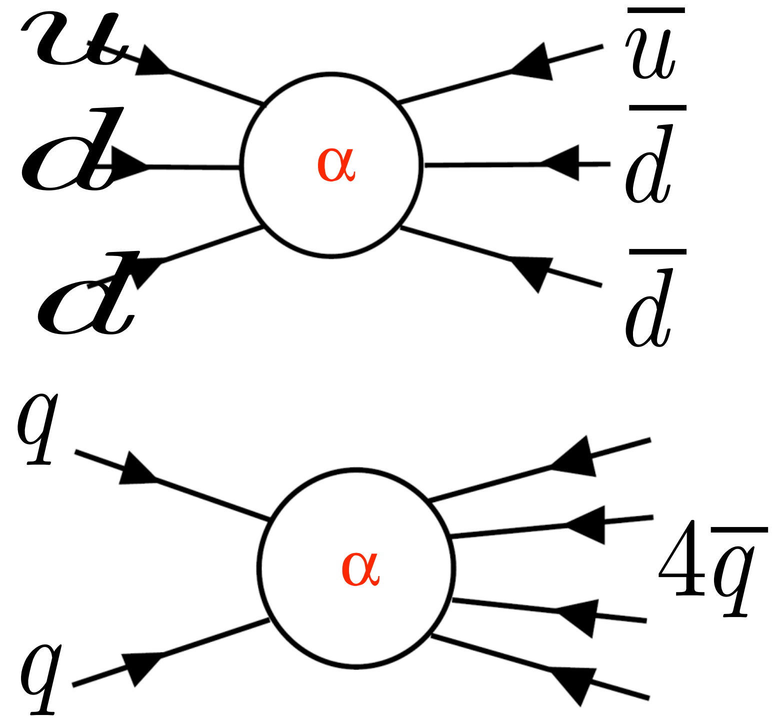
Theoretical nuclear NNbar suppression model is incomplete

Usual approach

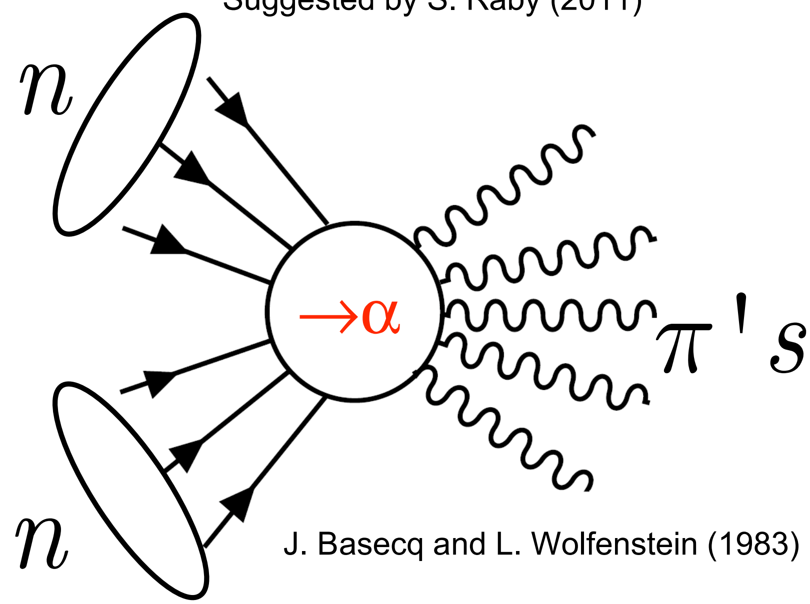


All these processes →
include the same amplitude α
and result in the same
indistinguishable final state
(of ~ 5 πs)

Existing intranuclear NNbar limits need to be re-evaluated



Suggested by S. Raby (2011)

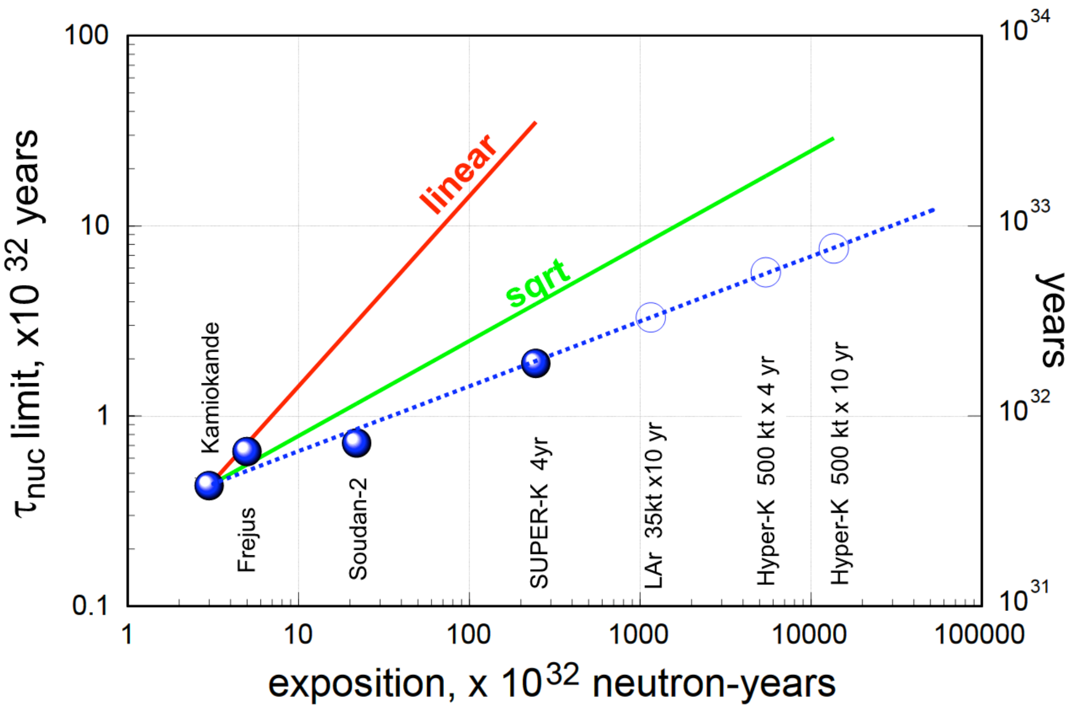


J. Basecq and L. Wolfenstein (1983)

Bound neutron N-Nbar search experiments

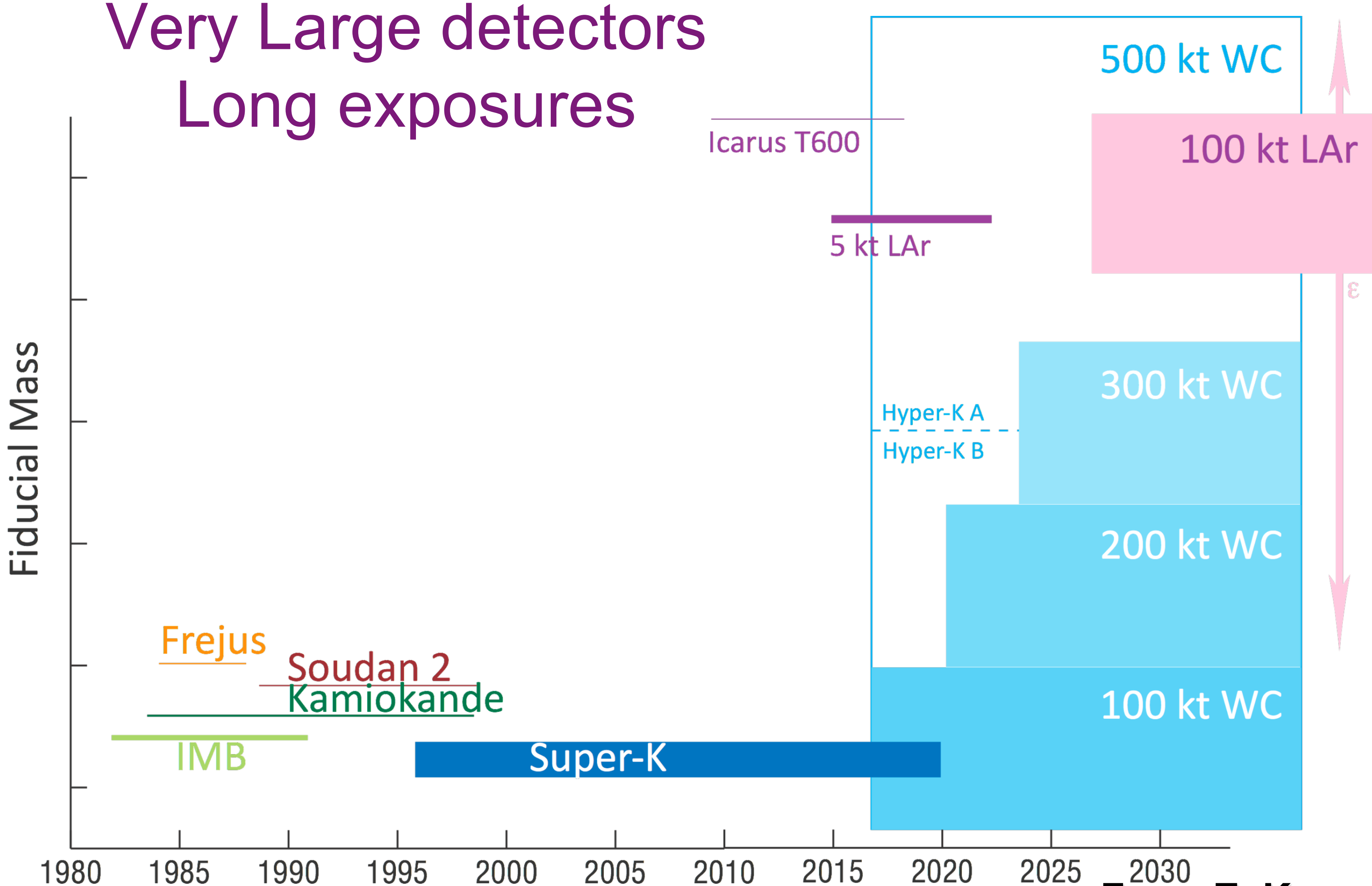
Experiment	Year	A	n·year (10^{32})	Det. eff.	Candid.	Bkgr.	τ_{nucl}, yr (90%
Kamiokande	1986	O	3.0	33%	0	0.9/yr	$>0.43\times10^{32}$
Frejus	1990	Fe	5.0	30%	0	4	$>0.65\times10^{32}$
Soudan-2	2002	Fe	21.9	18%	5	4.5	$>0.72\times10^{32}$
SNO *	2010	D	0.54	41%	2	4.75	$>0.301\times10^{32}$
Super-K	2011	O	245	12.1%	24	24.1	$>1.89\times10^{32}$

* Preliminary



- From Kamiokande to Super-K atmospheric ν background is about the same ~ 2.5 /kt/yr.
- Large D_2O, Fe, H_2O detectors are dominated by backgrounds; LAr detectors are unexplored
- Observed improvement is weaker than SQRT due to irreducible background and uncertainties of efficiency and background.
- Still possible to improve a limit but impossible to claim a discovery.

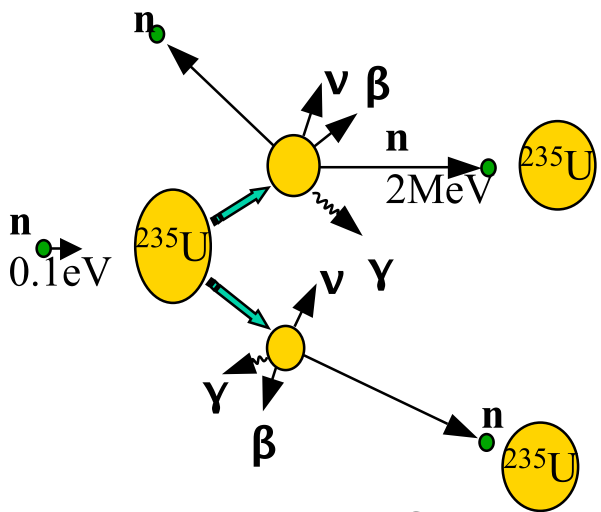
Very Large detectors
Long exposures

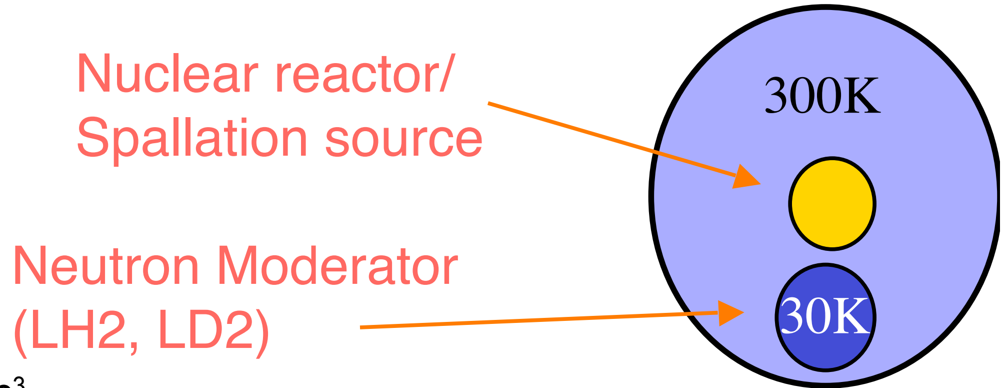


From E. Kearns

Can improved detector technology reduce the neutrino background for nnbar in nuclei?

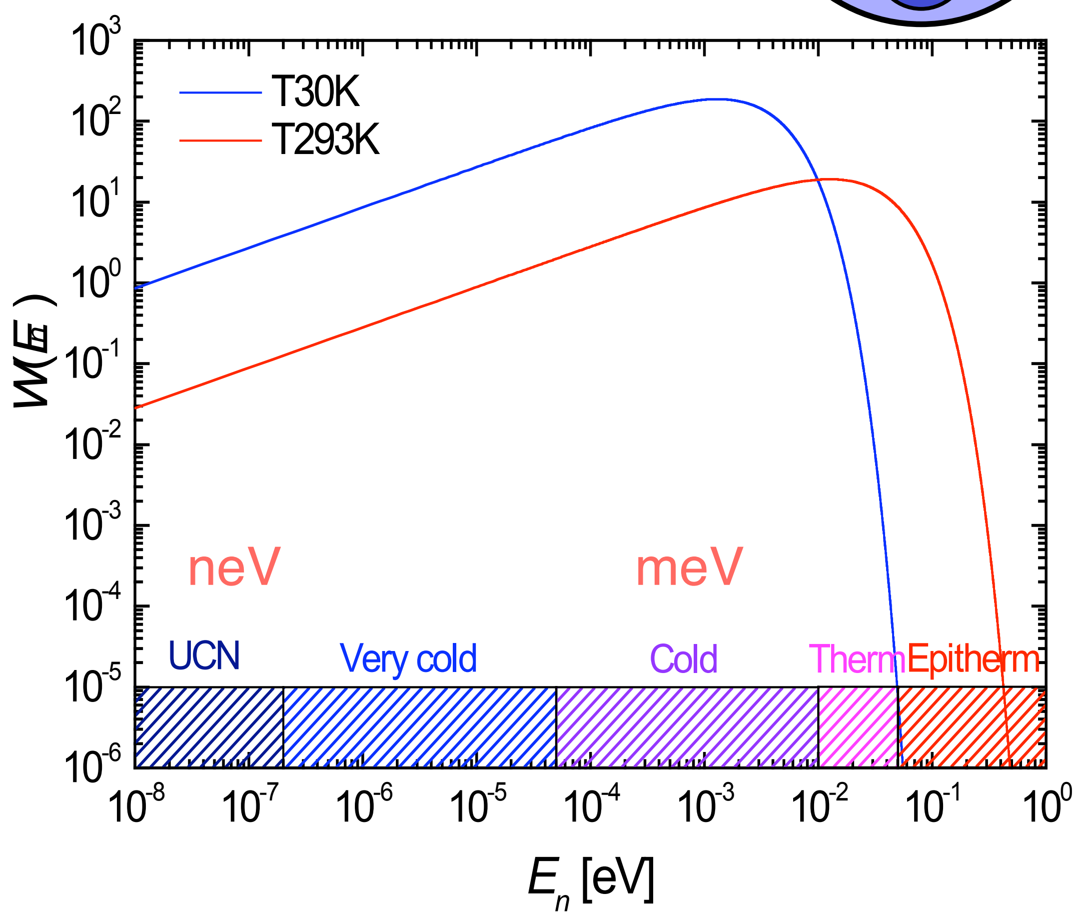
"Slow" Neutrons: MeV to neV



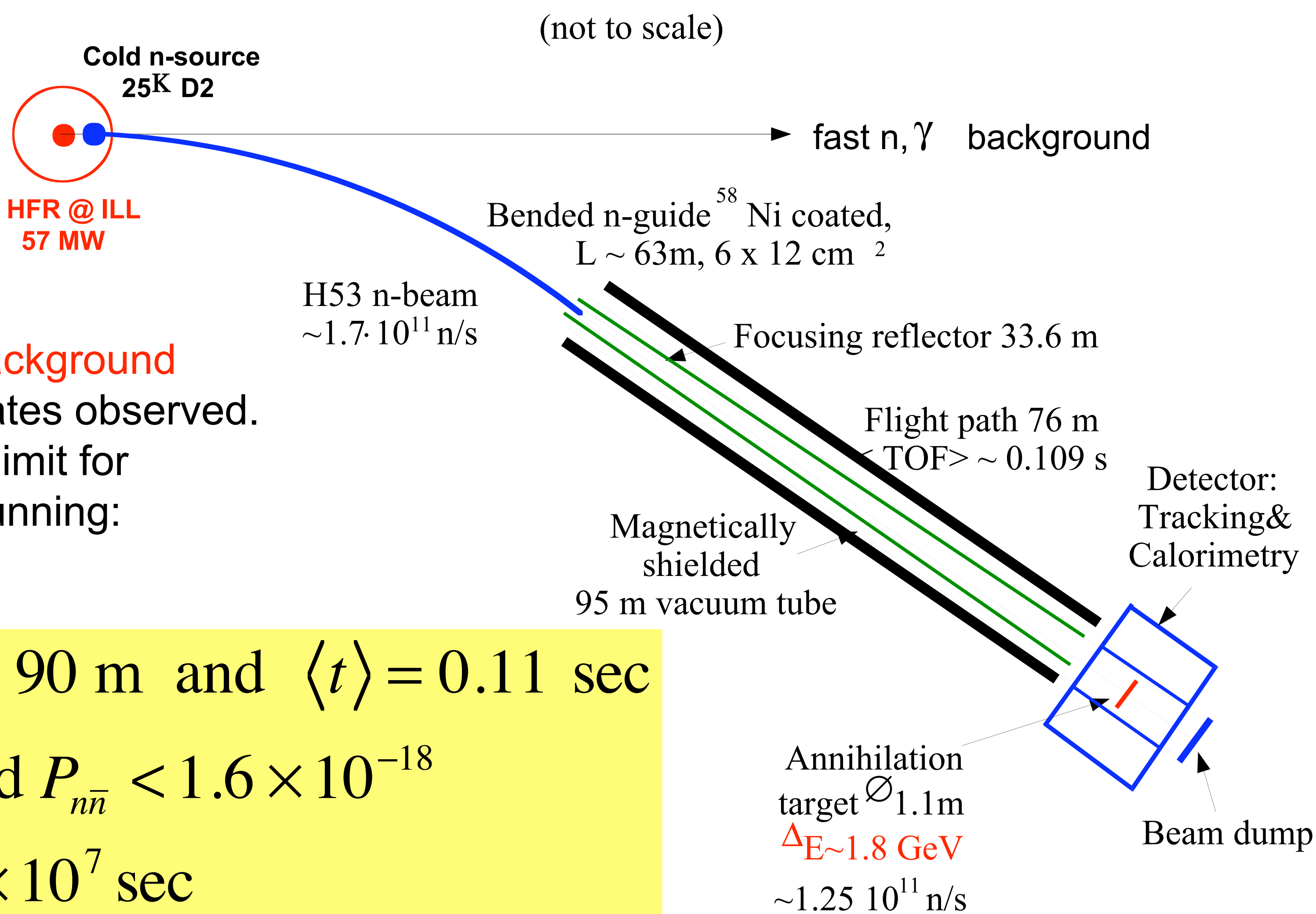


~MeV neutrons from fission or spallation, thermalized in ~ 20 collisions in ~ 100 μs

T (K)	E (meV)	λ (A)	v (m/sec)
300	25	1.6	2200
20	2	6.4	550



N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



No GeV background

No candidates observed.

Measured limit for

a year of running:

$$\text{with L} \sim 90 \text{ m and } \langle t \rangle = 0.11 \text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

$$\tau > 8.6 \times 10^{7} \text{ sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Quasifree Condition: B Shielding and Vacuum

$\mu B t \ll \hbar$ ILL achieved $|B|<10$ nT over 1m diameter, 80 m beam,one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need $|B|<\sim 1$ nT

If nnbar candidate signal seen, easy to “turn it off” by increasing B

$V_{opt} t \ll \hbar$:

Need vacuum to eliminate neutron-antineutron optical potential difference.

$P<10^{-5}$ Pa is good enough, much less stringent than LIGO

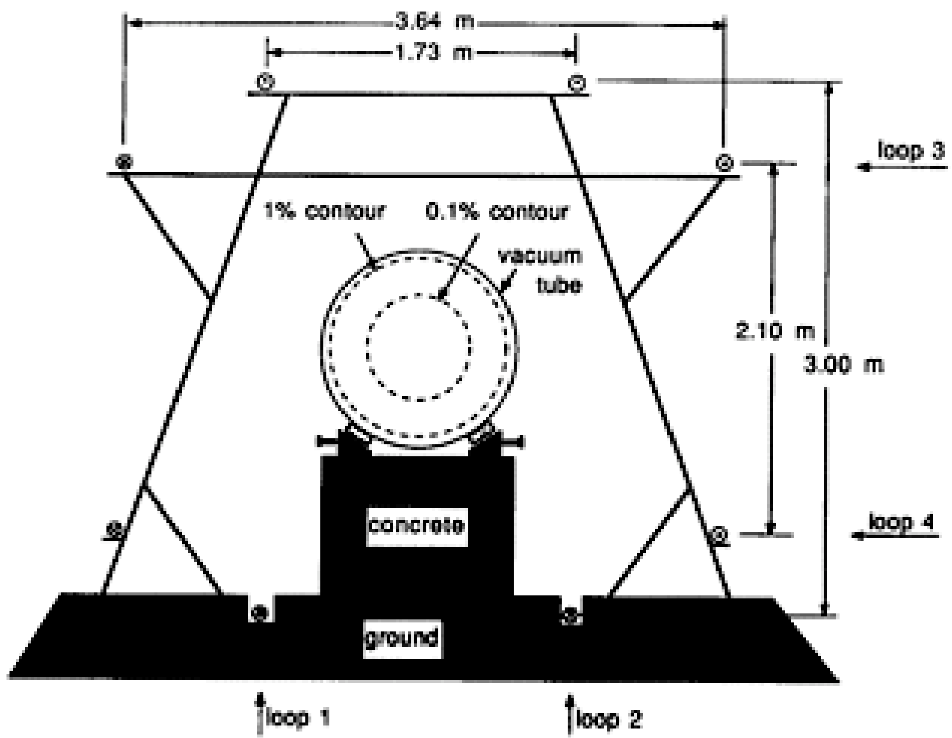
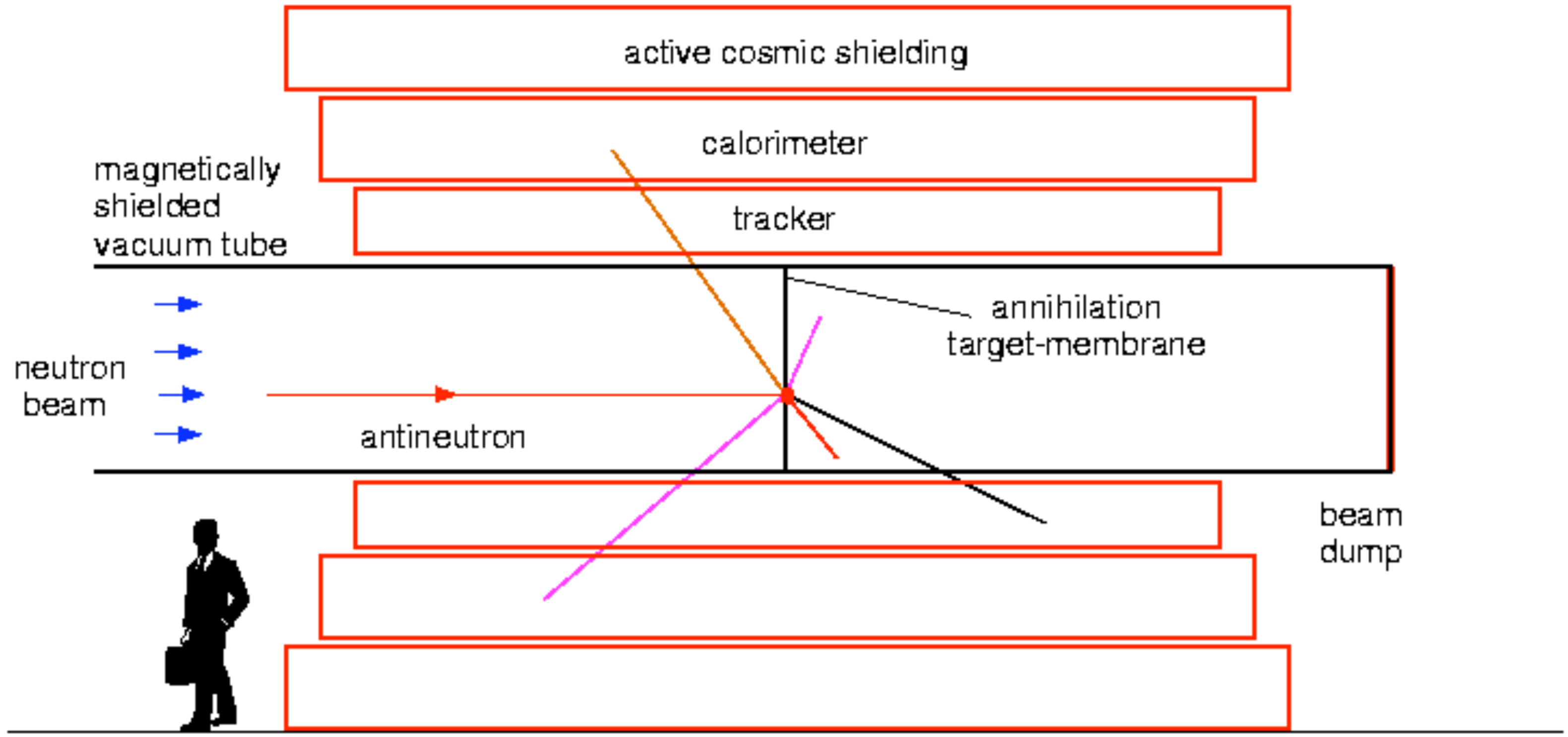


Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

The conceptual scheme of antineutron detector



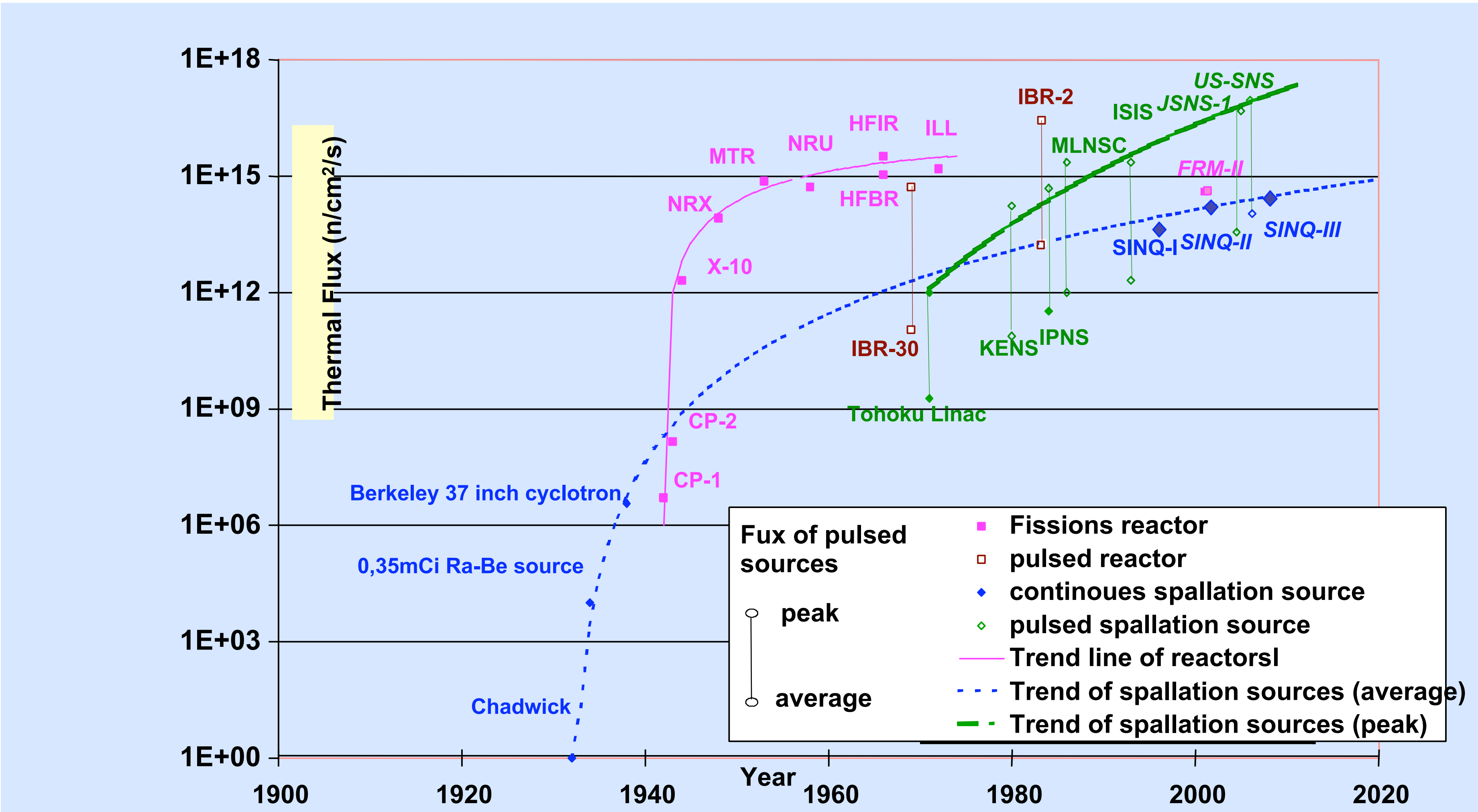
$$\boxed{\bar{n} + A \rightarrow \langle 5 \rangle \; pions \quad (1.8 \text{ GeV})}$$

Annihilation target: ~100μ thick Carbon film

$\sigma_{\text{annihilation}} \sim 4$ Kb $\qquad \sigma_{\text{nC capture}} \sim 4$ mb

vertex precisely defined. No background was observed

How to Improve the Experiment? Not so Easy.
Max neutron flux/brightness: ~unchanged for ~4 decades

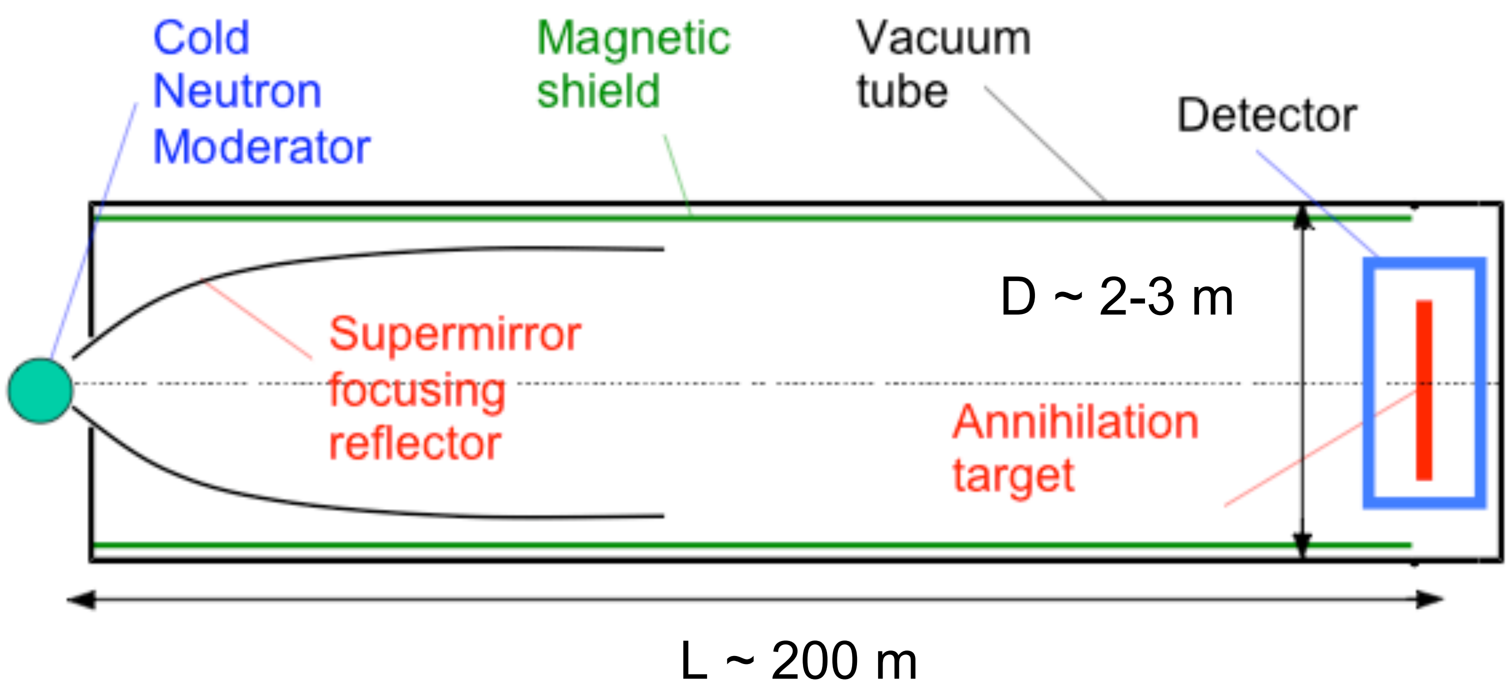


Neutron flux is increasing only slowly with time R. Eichler, PSI

Better Free Neutron Experiment (Horizontal beam shown: vertical possible)

need slow neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible with existing n optics technology (see G. Greene talk)



NNbar Summary

New physics beyond the SM can be discovered by NNbar search

Improvement in free neutron oscillation probability of a factor of ~1,000 is possible

If discovered:

- n$\rightarrow$nbar observation would violate B-L by 2 units, establish a new force of nature, illuminate beyond SM physics, and may help to understand matter-antimatter asymmetry of universe

If NOT discovered:

- will set a new limit on the stability of “normal” matter via antimatter transformation channel. Will constrain some scenarios for B-L violation and “post-sphaeleron” baryogenesis

Summary

New physics beyond the Standard Model can be discovered by NNbar search

Experiments with free neutrons possess very low backgrounds (sharp vertex localization): ILL experiment observed no background. Interpretation of result is independent of nuclear models. Any positive observation can be turned off experimentally with the application of a small magnetic field.

Sensitivity of free neutron experiment for NNbar transition rate can be improved by factor of ~1000 using existing technology [Combination of improvements in neutron optics technology, longer observation time, and larger-scale experiment]. Further improvements in a free neutron experiment can comes from neutron optics technology development (see Geoff Greene talk).

US high-energy intensity frontier complex could in principle provide the type of dedicated source of slow neutrons needed for NNbar experiment.